was not mixed (top). Homogeneity in these images indicates that the distribution of lifetimes (of the reaction product) in the flow is narrow and that there is little axial dispersion. Thus, this example demonstrates the benefit of using aspects of the present invention to increase conversion efficiency in a laminarly flowing reactive system.

EXAMPLE 5

[0059] **FIGS. 9***a-b* shows axial dispersion with and without efficient mixing and demonstrates the reduction of dispersion of a plug of miscible solution in a chaotically stirred Poiseuille flow (**FIG. 9***b*) relative to an unstirred Poiseuille flow (**FIG. 9***a*).

[0060] **FIG. 9***a* shows unstirred Poiseuille flow in a rectangular channel that is 21 cm×200×70 μm^2. **FIG. 9***b* shows stirred flow in a staggered herringbone mixing apparatus that is 21 cm×200×85 μm^2. A plug of fluorescent dye was introduced into both structures. The traces represent the time evolution of the total fluorescence intensity as observed with a fluorescence microscope having 5× lens that averages over the cross-section of the channel at positions 0.20 cm (**100**), 0.62 cm (**102**), 1.04 cm (**104**), 1.46 cm (**106**), and 1.88 cm (**108**) downstream from the entrance of the channel. These distances corresponded to 10, 30, 50, 70, and 90 mixing cycles, respectively. In the unstirred case, **FIG. 9***a*, the plug was distorted and spread over most of the length of the channel. In the chaotically stirred flow, **FIG. 9***b*, the plug retained its shape and broadened only mildly. The appropriate fluid flow parameter were calculated to be U_a~0.3 cm/s; Pe~1.5×10^4; L_{max}/h=20 cm/80 μm=2500.

[0061] **FIG. 9***a* illustrated that for high Pe, the width of a plug in an unstirred Poiseuille flow grew linearly with time at the maximum flow speed, U_{max} (the fluid at the center of the channel moves at U_{max} while fluid at the walls is stationary); this rapid broadening will continue for a distance down the channel, L~hPe. The traces record the total fluorescence intensity, integrated over the cross-section of the channel, as a function of time at equally spaced positions along the channel.

[0062] In the absence of stirring, the initial distribution of fluorescence rapidly distorted. The peak intensity also drastically reduced. The plugs developed long tails due to the fluorescent solution that was trapped in the slowly moving regions of the flow near the walls. This effect, it is believed, is detrimental for the transfer of discrete plugs of fluid in laminar flows in channels and pipes.

[0063] In contrast, in chaotically stirred flow, shown in **FIG. 9***b*, a plug of solution broadened more slowly because, it is believed, volumes of the solution moved between fast and slow regions of the flow. Thus, the broadening of a plug should rapidly become diffusive, i.e., it is believed that the broadening is proportional to $\sqrt{t}$ and should occur after n_m cycles with an effective diffusivity, D_{eff} that is a function of the molecular diffusivity and the characteristics of the flow as discussed by Jones et al. in *J. Fluid Mech,* 280, pp. 149-172 (1994), which is incorporated by reference in its entirety.

[0064] The traces shown in **FIG. 9***b* demonstrated improved reduction of dispersion in a flow that was stirred in a mixing apparatus with a staggered herringbone structure, i.e., chaotically stirred flow. As shown in **FIG. 9***b*, in the chaotically stirred flow, the shape of the distribution of fluorescence was largely maintained, and the peak intensity dropped gradually.

[0065] Those skilled in the art would readily appreciate that all parameters and configurations described herein are meant to be exemplary and that actual parameters and configurations will depend upon the specific application for which the mixing systems and methods of the present invention are used. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. For example, those skilled in the art may recognize that the mixing apparatus of the present invention may be used to mix a fluid having a solid dissolving therein and that the present invention may be used to improve the transfer properties, heat or mass transfer, of a fluid flowing adjacent a surface having the features of the present invention. Moreover, the present invention can be seen to provide efficient mixing at low Reynolds numbers but should be effective for any non-turbulent flow, Reynolds number less than about 2300, and need not be restricted to a systems with Reynolds number less than 100 or with dimensions less 1000 μm.

[0066] It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, the invention may be practiced otherwise than as specifically described. The present invention is directed to each individual feature, system, or method described herein. In addition, any combination of two or more such features, systems or methods, if such features, systems or methods are not mutually inconsistent, is included within the scope of the present invention.

What is claimed:

1. An article comprising a microfluidic channel defined therein designed to have fluid flow therethrough in a principal direction, the microfluidic channel including a channel surface having at least one groove or protrusion defined therein, the at least one groove or protrusion having a first orientation that forms an angle relative to the principal direction.

2. The article of claim 1, wherein the microfluidic channel has at least one of a width and a depth that is less than about 1000 μm.

3. The article of claim 2, wherein the microfluidic channel has at least one of a width and a depth that is less than about 500 μm.

4. The article of claim 3, wherein the microfluidic channel has at least one of a width and a depth that is less than about 200 μm.

5. The article of claim 1, wherein the substrate comprises a polymer.

6. The article of claim 1, wherein the angle is less than about 90 degrees.

7. The article of claim 1, wherein the groove or protrusion has a depth that is less than a width of the microfluidic channel.

8. The article of claim 1, wherein the groove or protrusion has a depth that is less than a depth of the microfluidic channel.

9. The article of claim 1, wherein the groove or protrusion has a width that is less than a width of the microfluidic channel.